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DEVELOPMENT OF A FRESHWATER GEOMAGNETIC ELECTROKINETOGRAPH

by

Bruce D. Blakkan

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ABSTRACT

A Freshwater Geomagnetic Electrokinetograph for measuring surface current velocities in large bodies of fresh water, such as the Great Lakes, is described. An antimony-antimonous oxide electrode, which has been developed for use with the Freshwater GEK, is evaluated, and detailed instructions for its fabrication are given in the Appendix. An equation, which relates surface current velocities to e.m.f. signals, is developed on the basis of electromagnetic theory. The GEK was tested in the Grand Traverse Bay region of Lake Michigan; the results of these tests are shown to compare favorably with drogue measurements.

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INTRODUCTION

An electromagnetic method for measuring current velocities from a ship under way in the open water of the oceans has been developed and used in saltwater research for more than a decade.[1,2] The measurements are made with a device, termed "Geomagnetic Electrokinetograph" (or more simply, "GEK"), which senses electromagnetic effects associated with the water's motion through the earth's magnetic field. The purpose of the research reported herein has been to develop a similar technique for use in fresh water, particularly in the Great Lakes.

ELECTRODES

The GEK requires a pair of electrodes for making electrical contact with the water; the electrochemical potential associated with the electrodes must remain nearly constant.* A silver-silver chloride electrode is used with the saltwater GEK. This electrode

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*See section on "Electromagnetic Effects."

represents one of the most stable electrochemical systems and is particularly suited to saltwater research because of the large and nearly constant chloride ion concentration in the oceans. However, due to the relatively low concentration of this ion in fresh water the Ag-AgCl electrode is unstable therein; the electrochemical potential does not remain constant. The primary problem in developing a freshwater GEK is that of fabricating a constant-voltage electrode. (For the Great Lakes: constant ± 0.3 mv during each measurement is sufficient.*)

An antimony-antimonous oxide electrode in a buffer-agar solution has been developed for the freshwater GEK. Detailed instructions for its fabrication are given in the Appendix. The net electrochemical potential, V_e, associated with an electrode pair of this design will depend principally on temperature, concentration of the various ions in the electrolyte, and the nature of the liquid junctions between the electrolyte and <u>in situ</u> water. V_e for the electrodes will remain constant, within the tolerable ± 0.3 mv, during any particular current velocity measurement if the electrodes are fabricated properly.

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*See section on "Electromagnetic Effects."

It is necessary to consider the effects of changing environmental conditions on the potential of an electrode pair. It can be shown that the potential of an Sb-Sb_2O_3 electrode relative to the reversible hydrogen electrode is given by the expression:

$$e_{sb} = e_o + 2.303(R \cdot T/F)(pH)$$

where R, T, F, pH, and e_o are, respectively, the universal gas constant, absolute temperature, the Faraday, negative logarithm to the base ten of the hydrogen ion concentration, and the electrode potential when T = 298.16°K and pH = 0. e_o depends upon temperature only.[3]

It is seen from the above equation that the electrode potential depends directly on the pH of the electrolyte involved. The pH must remain constant if the electrode potential is to be constant (at constant temperature). For the electrodes described in the Appendix a high concentration pH-7 buffer solution is used as the electrolyte in the vicinity of each electrode; since the electrodes, surrounded by this electrolyte, are to be immersed in water there will be a tendency for the buffer to diffuse away from the neighborhood of the electrodes; the electrolyte concentration will then decrease with time, resulting in a less effective buffer at the electrode surface (and

increased electrical resistance of the electrode system*). The diffusion process is retarded by dissolving the buffer in an agar solution, pouring the solution around the electrode and allowing the electrode to become immobilized in the buffer-agar gel when it solidifies.

The agar gel provides the electrode with a very uniform, solid-electrolyte environment. Thus any other changes, in addition to those due to diffusion of the electrolyte, which might normally take place, were the electrode in a fluid rather than solid medium, are minimized.

The electrode potential also depends upon temperature. However, it can be shown on the basis of electrochemical theory that the magnitude of the temperature coefficient is less than 0.1 mv per centigrade degree. No attempt has been made to measure this temperature dependency in the laboratory because the GEK electrodes are used in a nearly constant temperature environment. Horizontal temperature gradients in the Great Lakes are relatively small. A thermistor was attached to the forward electrode of the GEK cable while "GEKing" in Grand Traverse Bay on Lake Michigan during the months of July and August (1962); temperature was determined by

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*See section on "Electromagnetic Effects."

measuring the resistance of the thermistor with a d-c wheatstone bridge circuit. The temperature of the water at the level of the electrodes remained constant during every current velocity measurement. Since the accuracy of the thermistor was better than $\pm 0.2C^\circ$ this value was taken as the upper limit of temperature variability; the potential change corresponding to $0.2C^\circ$ is less than 0.02 mv, one-tenth of the tolerable potential variability.* For this application a pair of electrodes would not have a net temperature coefficient larger than that of one individual electrode.

A pair of electrodes is used with the GEK. The individual electrode potentials oppose each other in the circuit, but there is always a net e.m.f., V_e, due not only to the fact that no two electrodes are identical, but also to the existence of liquid junctions in the circuit. The contribution to V_e due to the slight dissimilarity between electrodes can be studied by encasing two antimony slugs in a common buffer-agar electrolyte; the magnitude of the potential (seldom larger than 50 mv) will be different for each pair of electrodes. This component of V_e varies slowly and steadily at a rate of less than five microvolts per minute; it is too small a

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*See section on "Electromagnetic Effects."

potential drift to give rise to any significant error in current velocity measurements.

The second source of potential contributing to V_e is that associated with the liquid junctions between the buffer solutions and the <u>in situ</u> water. These boundary potentials oppose each other in the circuit, the net e.m.f. being less than 1.0 mv. This net junction potential varies sporadically as the electrodes are towed through the water; the variability is within ± 0.2 mv, slightly less than the desired tolerance of ± 0.3 mv.

When fabricating electrodes for the GEK it is advisable to prepare several electrodes (six or more) and to select the (encased) pair with the lowest electrochemical potential. If n electrodes are available, then N different electrode pairs are possible, where $N = [n!/2!(n-2)!]$.[4] V_e for each pair is measured and the pair with the smallest value of V_e should be selected. The electromagnetically induced e.m.f., V_I, is seldom larger than a few millivolts so since V_e is measured along with V_I, V_e should be at least within one order of magnitude of V_I.* Values of V_e up to 15 or 20 mv are acceptable.

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*See section on "Electromagnetic Effects."

Tests, to determine the upper limit of variability of V_e for many electrode pairs, have been made in the laboratory and from aboard ship. The only noticeable variations while making current measurements are due principally to changes in the velocity at which the electrodes are being towed through the water. Properly designed electrodes will maintain constant potential, ± 0.3 mv, for velocity changes as great as ± 2 knots when the ship's speed is in the neighborhood of 10 knots. Although the electrodes' speed through the water is greatly reduced on turns, and hence the potential may be changed by more than ± 0.3 mv (not more than 1.0 mv), the potential returns to its original value shortly after the turn is completed.

It has been particularly helpful in evaluating electrodes to tow the GEK cable from the ship on days when there is no significant current (as is indicated by drogues as well as by the GEK itself), no waves and no wind. Under these conditions, V_e is the only potential recorded and its behavior in the actual working environment can be determined.

Electrodes can also be subjected to tests in the laboratory to determine whether the potential remains constant at a given towing speed. In the Great Lakes Research Division Laboratory the electrodes are placed in a tank in which water is being circulated at a given velocity by means of an outboard motor propeller

powered by an electric motor. The electrode pair potential remains constant ±0.3 mv under the most severe conditions of turbulence.

It has been found that the slight variations in V_e can usually be discerned from those due to electromagnetic effects by carefully analyzing GEK data. If the temperature is continuously monitored, it may be possible to distinguish between those changes in V_e due to temperature and those due to other factors.

It should be noted that a silver-silver chloride electrode might be used in place of the antimony-antimonous oxide electrode if the buffer solution is replaced with a solution of high chloride ion concentration. The electrode design given in the Appendix could be used. The Ag-AgCl electrode would, theoretically, be more stable than the $Sb-Sb_2O_3$ electrode. The antimony electrode has been used with the freshwater GEK because it was thought that the <u>in situ</u> water, being a buffer solution, could serve directly as the electrolyte. However, it was found that the <u>in situ</u> water has a slightly high pH (pH 8), and in addition is a buffer solution of insufficient concentration. Since a technique for fabricating high quality antimony electrode slugs had already been developed, the author decided to continue using this type of electrode for the research reported herein.

The Ag-AgCl electrode in NaCl-agar solution will undoubtedly be used in the future.

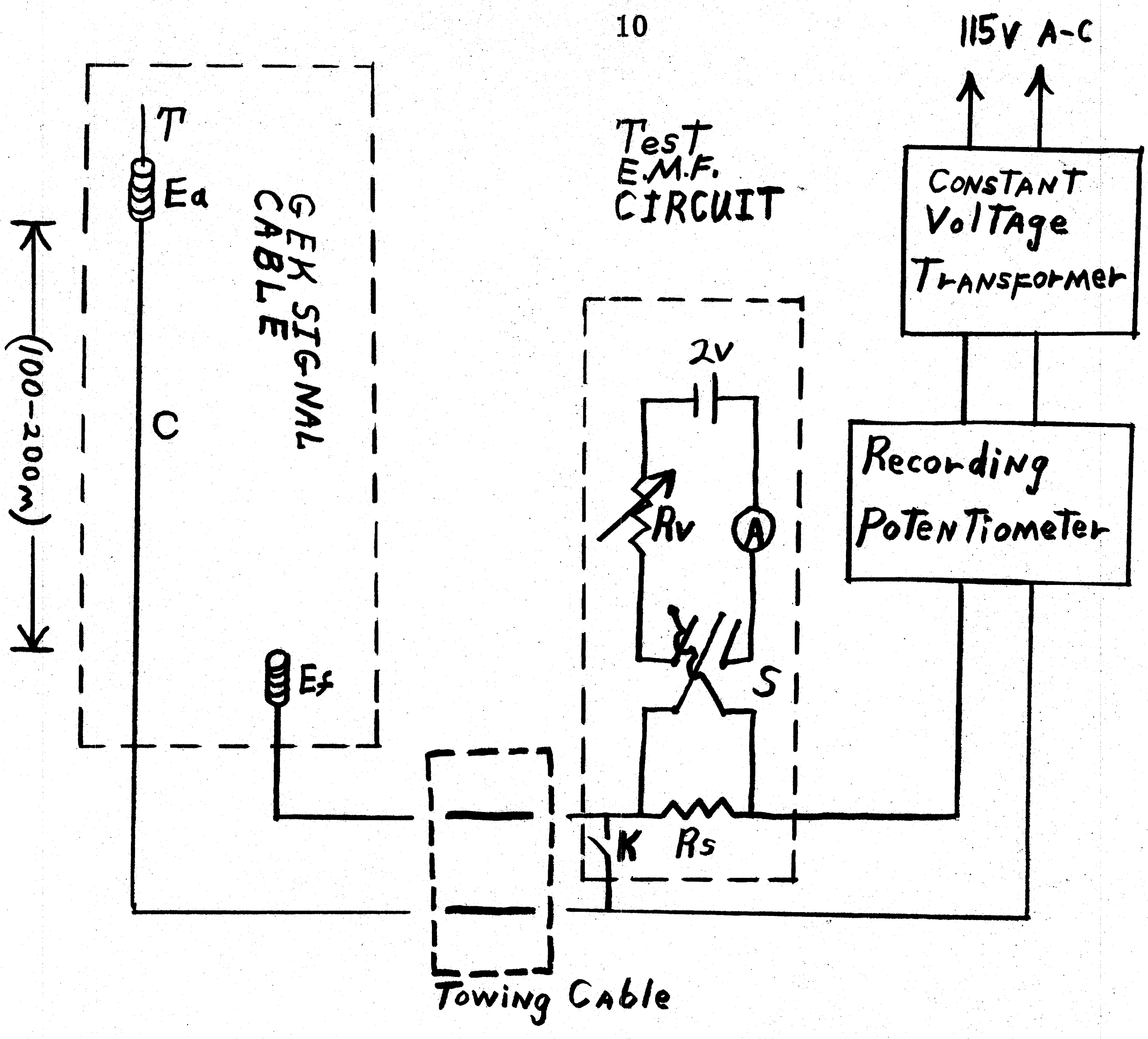
Other reversible electrodes, with appropriate electrolytes, might also be used if the principle of immobilizing the electrode in an agar gel is followed.

GEK CABLE AND MEASURING APPARATUS

The freshwater GEK measuring system consists of a signal cable, constant depth fish or weight, towing cable, standard test e.m.f. circuit, recording potentiometer, and a constant voltage transformer to maintain a constant 115 v a-c potential for the recording potentiometer. See Figures 1, 2, and 3.

The a-c power aboard some oceanographic vessels is subject to fluctuations in voltage, and in addition there are often d-c leakage currents in the power lines. It is well to power the recording potentiometer from a constant voltage transformer which will provide constant voltage and also act as an isolation transformer for the recorder.

The recorder to be used must be equipped with range changing and zero suppression circuits. The suppression feature allows the median signal, V_e, to be displaced to the center of the chart, whereas the range changing feature allows the changing part



S: a double pole double throw switch for reversing polarity of the test e.m.f.

K: a shorting switch.

E_a and E_f: the aft and fore electrodes, respectively.

T: 5 meters of trail wire to steady E_a while towing.

R_s: a standard one ohm resistor.

R_v: a variable resistor 5,000 ohms max.

A: a (0 to 5) ma milliameter.

C: signal conductor.

Fig. 1.—Schematic diagram of GEK measuring system.

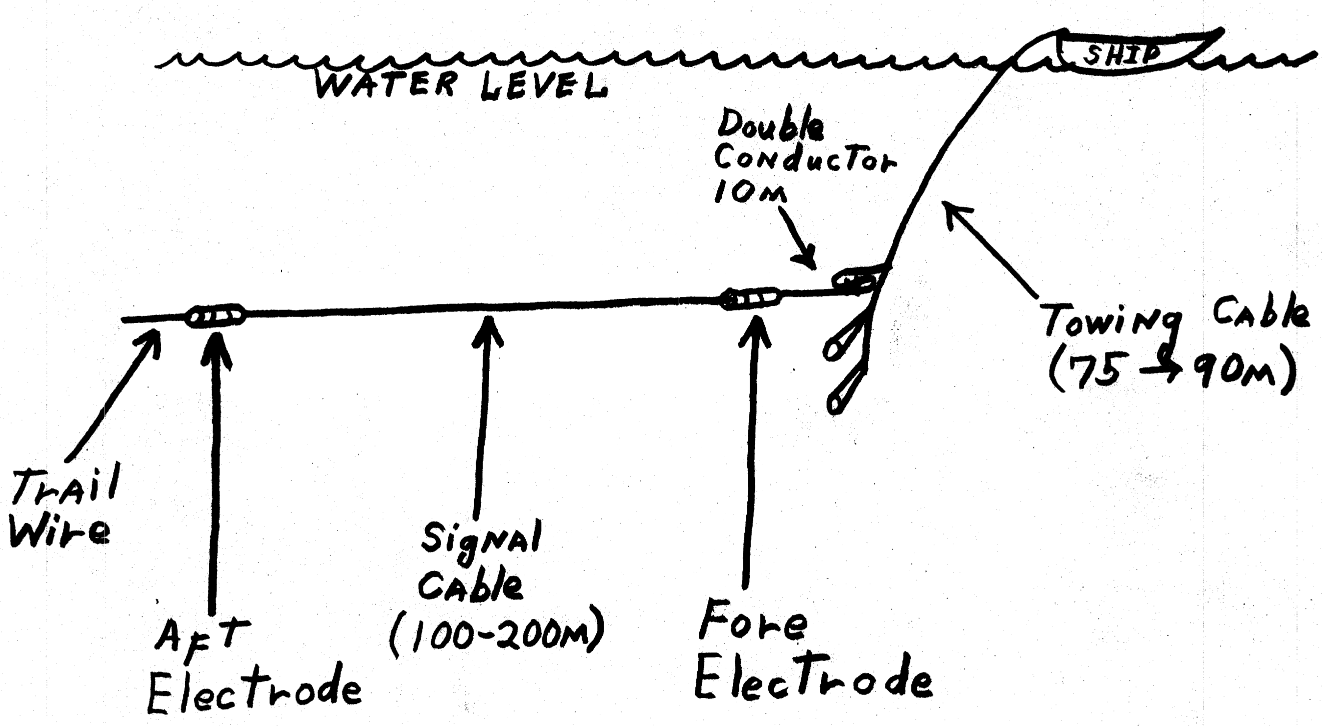
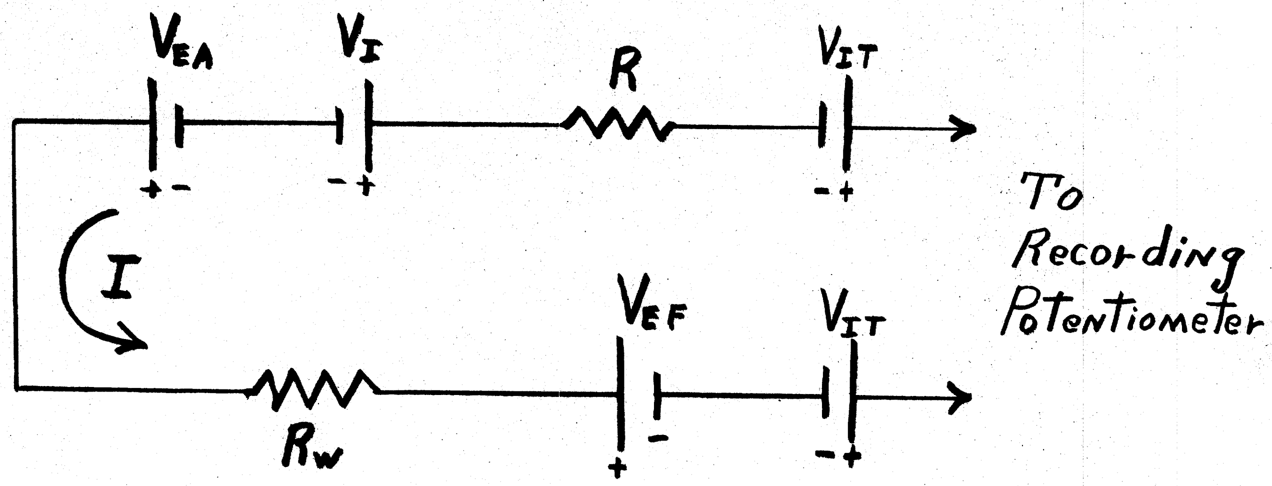


Fig. 2.—Signal cable system as towed by ship.



I: the electric current which flows through the circuit (~0 since a potentiometer is used to measure the net potential).

R_w: resistance of the water path.

R: resistance of the cables, etc.

V_{ea} and V_{ef}: the electrochemical potentials of aft and fore electrodes, respectively ($V_e = V_{ea} + V_{ef}$).

V_I: the induced signal, due to electromagnetic induction as the signal cable drifts through the earth's magnetic field.

V_{IT}: the induced e.m.f. in one towing cable conductor; the two values of V_{IT} denoted in the circuit diagram, each of which is associated with one of the two towing cable conductors, oppose each other in the circuit, the net effect being zero.

Fig. 3.—Diagram of GEK signal cable circuit.

(± maximum V_I) of the total voltage to be adjusted to the full width of the chart in order to give better accuracy. Maximum accuracy in measuring current velocities can be attained only with these features. The measurements made to date were with a Leeds and Northrup Speedomax H-AZAR (adjustable zero adjustable range) Recording Potentiometer. The chart speed was 1-1/3 inches per minute and it was found that Leeds and Northrup Chart Paper No. 600186 greatly facilitated data analysis. This particular recorder was equipped with a chart tear-off device which was very useful. The external circuit resistance, for this recorder, was limited to 2,500 ohms; this rather severe limitation had to be taken into account when designing the electrodes. The electrode design described in the Appendix is such that the circuit resistance including the towing cables and resistive water conduction path, as well as that of the electrode pair, is less than 2,000 ohms for "GEKing" in waters of the Great Lakes. Each time the electrode assemblies are towed through the water some buffer leaches out and is replaced by water; the electrical resistance of the electrode pair increases with use as a result of this lowering in concentration of the buffer solution, the total circuit resistance reaching the 2,500 ohm limit of the recorder after six to eight weeks of use. At this time the electrodes must be replaced. It is noted in the Appendix that the lifetime of a pair of

electrodes may be increased if they are stored in a buffer solution while not in use.

To facilitate setting up and checking out the measuring apparatus aboard ship, a testing e.m.f. with a range of zero to five millivolts was built into the circuit. The test e.m.f. was used for quickly testing the system for open circuits and excessive resistance. When the circuit resistance is too high (usually an indication of old electrodes) a very definite response time lag will be noticed on the recorder chart if the test e.m.f. is switched from positive to negative and back to a positive 2 to 5 mv value. The test e.m.f. and recorder could be calibrated against each other by closing the shorting switch K (see Fig. 1).

The GEK cable system used by the author during the summer of 1962 (see Fig. 2) consisted of a towing cable, constant depth weights, towing stocking, and signal cable with electrodes. The towing cable had a tensile strength greater than 6,000 lbs., and a length of 60 to 90 meters. This length was required in our case since the two 90 lb. conically shaped constant depth weights which were used were less than satisfactory in holding the signal cable to depths greater than 25 meters while towing at speeds of eight knots or more. (It is recommended that the constant depth weights be

replaced by a constant depth "fish" in order to reduce the length of the towing cable.)

The signal cable (500 lb. breaking strength) was double conductor back to the point where the forward electrode was electrically connected to one of these conductors. The cable was single conductor from there back to the after electrode, and a five meter trail wire was left attached astern of the aft electrode to keep this electrode from "fishtailing." It was necessary to take great care in attaching the signal cable to the towing cable; the conductors of the cable have a strong tendency to break at this point.

The signal is brought from the towing cable to the recorder circuit via a shielded cable. The towing cable need not be shielded.

ELECTROMAGNETIC EFFECTS

The Freshwater GEK is simply a conductor (the signal cable) drifting through the earth's magnetic field. The cable is attached to the ship and drifts at the same velocity as the ship (even though the cable is drifting through the stationary subthermocline water). As the cable drifts through the earth's magnetic field the voltage generated in the cable by electromagnetic induction is measured by means of a recording potentiometer. This induced e.m.f. is directly proportional to both the vertical component of the earth's magnetic

field and the component of drift velocity which is normal to the cable (but is independent of both the ship's forward speed relative to the water and the component of the ship's drift velocity parallel to the ship's heading). In order to better understand the relation between the induced e.m.f. and the surface current velocity it is necessary to consider the dynamic characteristics of the lake as well as the essential features of the GEK cable system. The relation between voltage and current velocity is calculated on the basis of electromagnetic theory.

It is believed that when a thermocline exists the transport velocity of the subthermocline water is negligible compared to the surface current velocity. Even when there is no thermocline it is not unreasonable to assume that at depths greater than 20 meters the transport velocity is much less than that of the water at the surface. There is, then, in general, a layer of moving water (above the thermocline) over a body of relatively motionless water (see Fig. 4). The surface water while in motion has an average velocity, $\bar{v}$, relative to the earth; and has nearly the same velocity relative to the earth's magnetic field. Potential gradients will be electromagnetically induced in this moving water since it is a conductor cutting the lines of force of a magnetic field. It is assumed that there are no such potential gradients set up in the subthermocline water

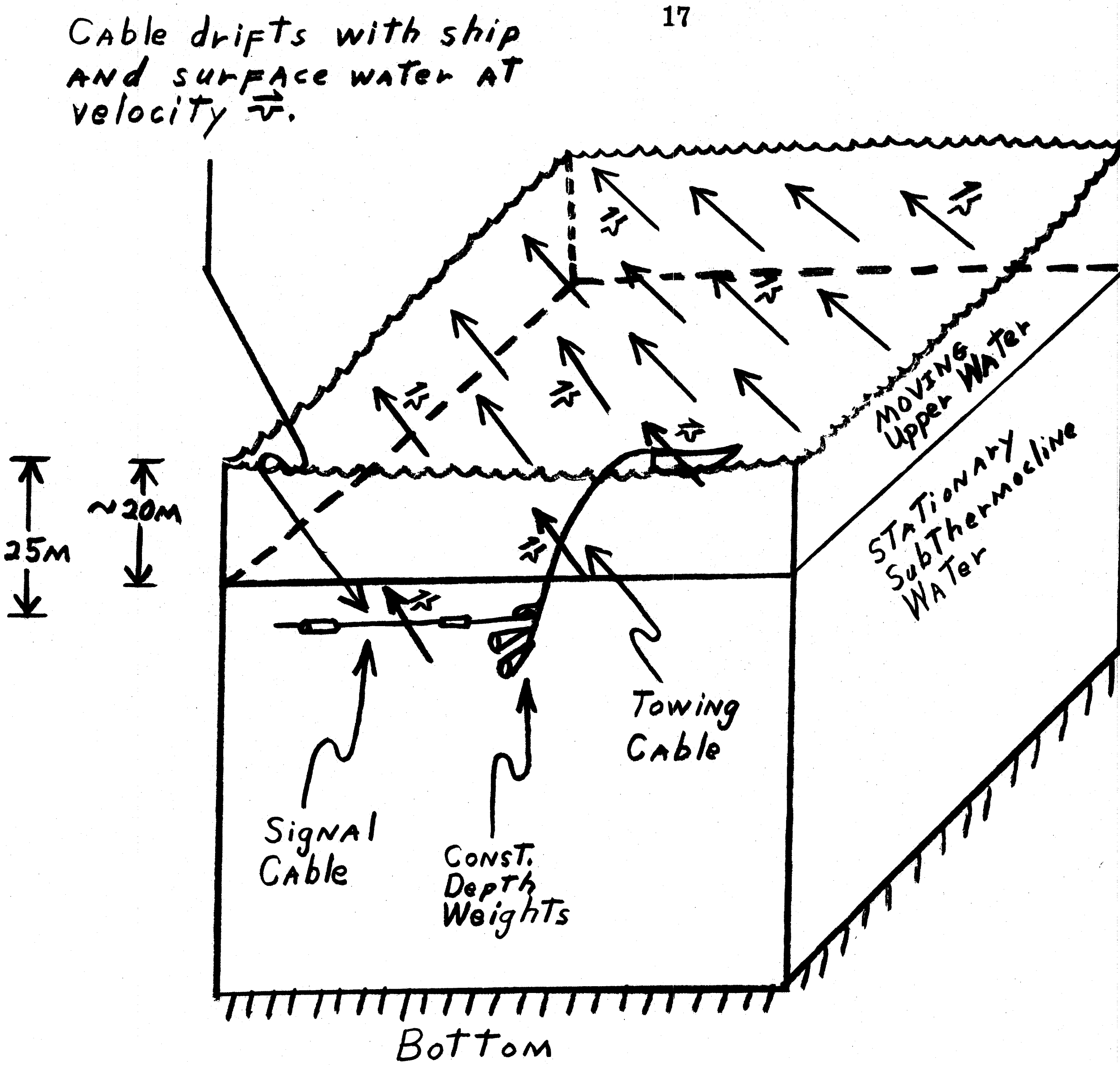


Fig. 4.—The cross section of a large freshwater lake in which the GEK is to be used. The ship and the GEK cable are assumed to drift with the surface water. The ship's forward velocity with respect to the water is not indicated here because the signal cable is assumed to at all times remain parallel to the ship's heading; it is assumed that the stationary subthermocline water exerts only negligible lateral drag on the signal cable and hence the cable tows straight behind the ship. Since $\overline{\ell}$ is assumed parallel to the ship's forward velocity, there is no potential induced in the cable due to this velocity.

(through which the GEK signal is towed) and in addition that those potential gradients in the moving water do not give rise to ohmic potential drops in the subthermocline water. It will be shown later that these assumptions are reasonable.

It is further assumed that the towing cable is of a length such that the signal cable is always towed through still water where there are no potential gradients. It is also assumed that the surface water is moving horizontally with a velocity $\bar{v} = v_x\bar{i} + v_y\bar{j} + 0 \cdot \bar{k} = v_x\bar{i} + v_y\bar{j}$, and that the GEK signal cable is always directly behind the boat and at all times parallel to the ship's velocity relative to the surface water.

Let $\bar{\ell}$ be the vector length of the signal cable—the head of the vector being at the forward electrode—and ℓ_x and ℓ_y be the projections of $\bar{\ell}$ on the north and east axes, x and y, respectively. See Figure 5. Then $\bar{\ell} = \ell_x\bar{i} + \ell_y\bar{j} + 0 \cdot \bar{k} = \ell_x\bar{i} + \ell_y\bar{j}$ where $\bar{i}$, $\bar{j}$, and $\bar{k}$ are unit vectors in the directions of the positive x, y, and z axes, respectively. Also let $\bar{H} = H_x\bar{i} + H_y\bar{j} + H_z\bar{k}$, where $\bar{H}$ is the vector denoting the earth's magnetic field. See Figure 5. Let $\bar{v} = v_x\bar{i} + v_y\bar{j} + v_z\bar{k}$ where $\bar{v}$ is the velocity at which the surface water, and hence the GEK signal cable, is moving with respect to the earth's magnetic field (assuming no drift of the ship due directly to wind); i.e., with respect to the earth's surface. Let V_I be the

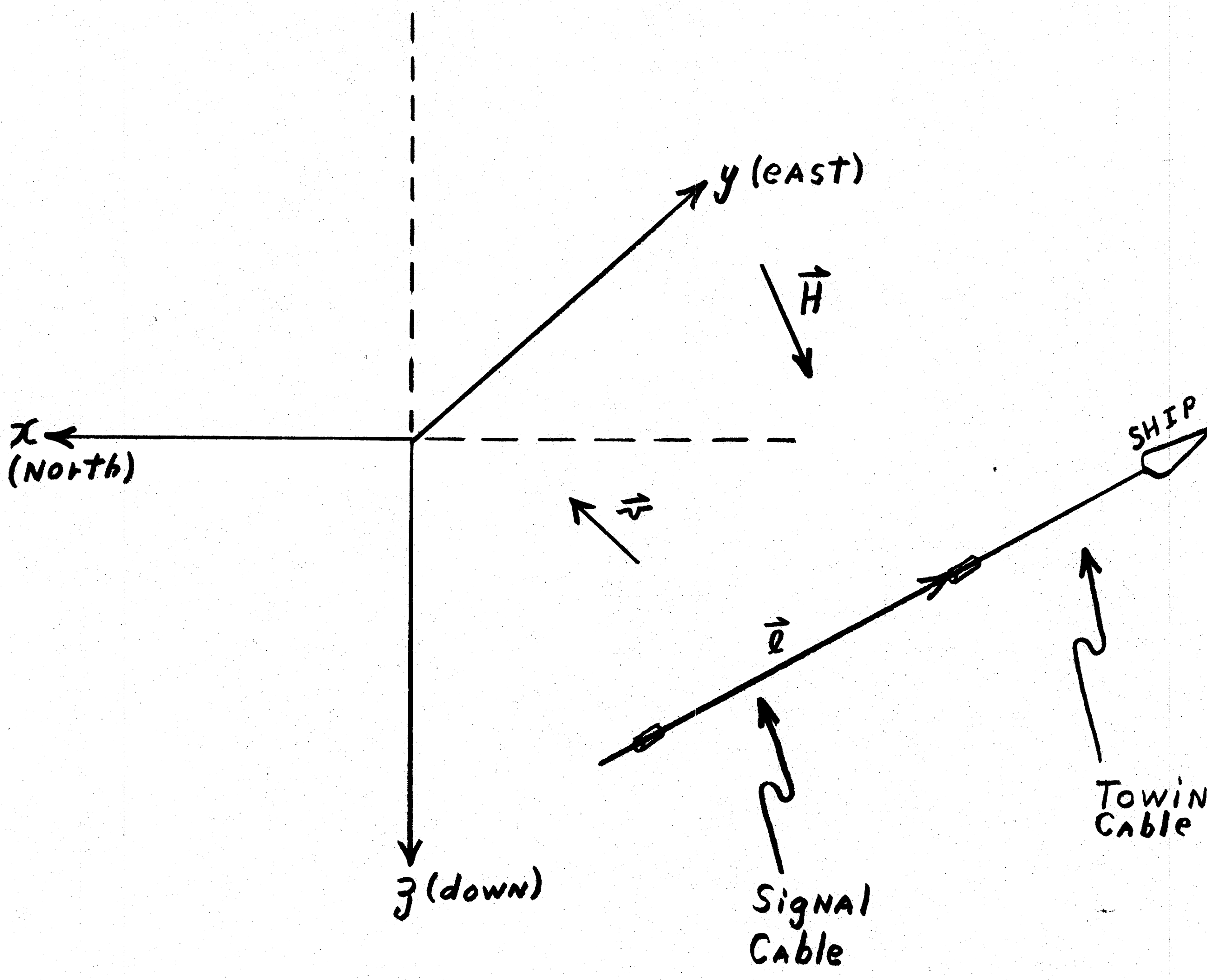

y (east)
$\vec{H}$
x (North)
SHIP
$\vec{v}$
$\vec{\ell}$
z (down)
Signal Cable
Towing Cable

Fig. 5.

potential difference between the ends of $\overline{\ell}$, considered positive in the sense of $\overline{\ell}$; this is the potential induced in the signal cable as it drifts with velocity $\overline{v}$ relative to the earth's magnetic field. By considering electromagnetic theory it can be shown[5] that

$$V_I = \overline{\ell} \cdot (\overline{v} \times \overline{H}).$$

(It should be noted at this point that if $\overline{v}$ is parallel to $\overline{\ell}$, that is if the velocity is parallel to the ship's heading, then $V_I = 0$; from this we conclude that the ship's forward velocity as well as the component of the ship's drift velocity which is parallel to the ship's heading do not give rise to an induced signal.) The vector product can be expanded, yielding:

$$V_I = \overline{\ell} \cdot [(v_y H_z - v_z H_y)\overline{i} + (v_z H_x - v_x H_z)\overline{j} + (v_x H_y - v_y H_x)\overline{k}].$$

Since $\overline{\ell}$ is always perpendicular to $\overline{k}$ and $v_z = 0$, it follows that

$$V_I = H_z(\ell_x v_y - \ell_y v_x).$$

(Note that V_I is independent of H_x and H_y.) The potentiometer will record a potential V_p which is the sum of V_e (the net electrochemical potential) and V_I.* That is:

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*The ohmic potential drops (see Figure 3) are here neglected since very little current is drawn by the potentiometer.

$$V_p = V_e + V_I = V_e + H_z\,(\ell_x v_y - \ell_y v_x).$$

H_z in the above equation is the vertical component of the earth's magnetic field intensity and can be considered constant during a particular current velocity measurement. ℓ_x, ℓ_y, and ℓ_z (ℓ_z is here zero) are specified by the length of the signal cable and the heading of the ship. There are then three unknowns (V_e, v_x, and v_y) in the expression for V_p. If the ship is headed successively along three different courses there will, for a given value of $\bar{v}$, be three different values of $\bar{\ell}$ ($\bar{\ell}_1$, $\bar{\ell}_2$, and $\bar{\ell}_3$), related by the three equations:

$$V_{p1} = V_e + H_z\,(\ell_{x1} v_y - \ell_{y1} v_x)$$

$$V_{p2} = V_e + H_z(\ell_{x2} v_y - \ell_{y2} v_x)$$

$$V_{p3} = V_e + H_z(\ell_{x3} v_y - \ell_{y3} v_x).$$

These three equations with three unknowns can be solved for v_x and v_y. Then:

$$v_x = \left[\frac{1}{H_z}\right]\left[\frac{(V_{p1}-V_{p2})(\ell_{x2}-\ell_{x3})-(V_{p2}-V_{p3})(\ell_{x1}-\ell_{x2})}{(\ell_{x1}-\ell_{x2})(\ell_{y2}-\ell_{y3})-(\ell_{y1}-\ell_{y2})(\ell_{x2}-\ell_{x3})}\right]$$

$$v_y = \left[\frac{1}{H_z}\right]\left[\frac{(V_{p2}-V_{p3})}{(\ell_{x2}-\ell_{x3})}\Big| + \Big|v_x\Big|\Big|\frac{(\ell_{y2}-\ell_{y3})}{(\ell_{x2}-\ell_{x3})}\right]$$

Here we have expressions for v_x and v_y in terms of known quantities. After v_x and v_y have been determined, their values can be substituted in any one of the three original equations to obtain V_e; there is, however, seldom any need to know the value of V_e.

If the coordinate system of Figure 5 is superimposed upon the mariner's compass rose (see Fig. 6), then $\ell_x = \ell \cos(\delta)$ and $\ell_y = \ell \sin(\delta)$. The above equations for v_x and v_y then become:

$$v_x = \left[\frac{1}{\ell H_z}\right] \times$$

$$\left\{\frac{[V_{p1}-V_{p2}][\cos(\delta_2)-\cos(\delta_3)]-[V_{p2}-V_{p3}][\cos(\delta_1)-\cos(\delta_2)]}{[\cos(\delta_1)-\cos(\delta_2)][\sin(\delta_2)-\sin(\delta_3)]-[\cos(\delta_2)-\cos(\delta_3)][\sin(\delta_1)-\sin(\delta_2)]}\right\}$$

$$v_y = \left[\frac{1}{\ell H_z}\right]\left\{\frac{[V_{p2}-V_{p3}]}{[\cos(\delta_2)-\cos(\delta_3)]}\right\}+\left[v_x\right]\left\{\frac{[\sin(\delta_2)-\sin(\delta_3)]}{[\cos(\delta_2)-\cos(\delta_3)]}\right\}$$

where $\overline{v} = v_x\overline{i} + v_y\overline{j}$. These equations are very useful in this form. One should be cautioned that the signs of the trigonometric functions will depend upon δ.

When "GEKing," each course should be held for approximately six minutes after the turn is completed. The aft electrode is to be electrically connected to the positive terminal of the recording potentiometer. The following information should be

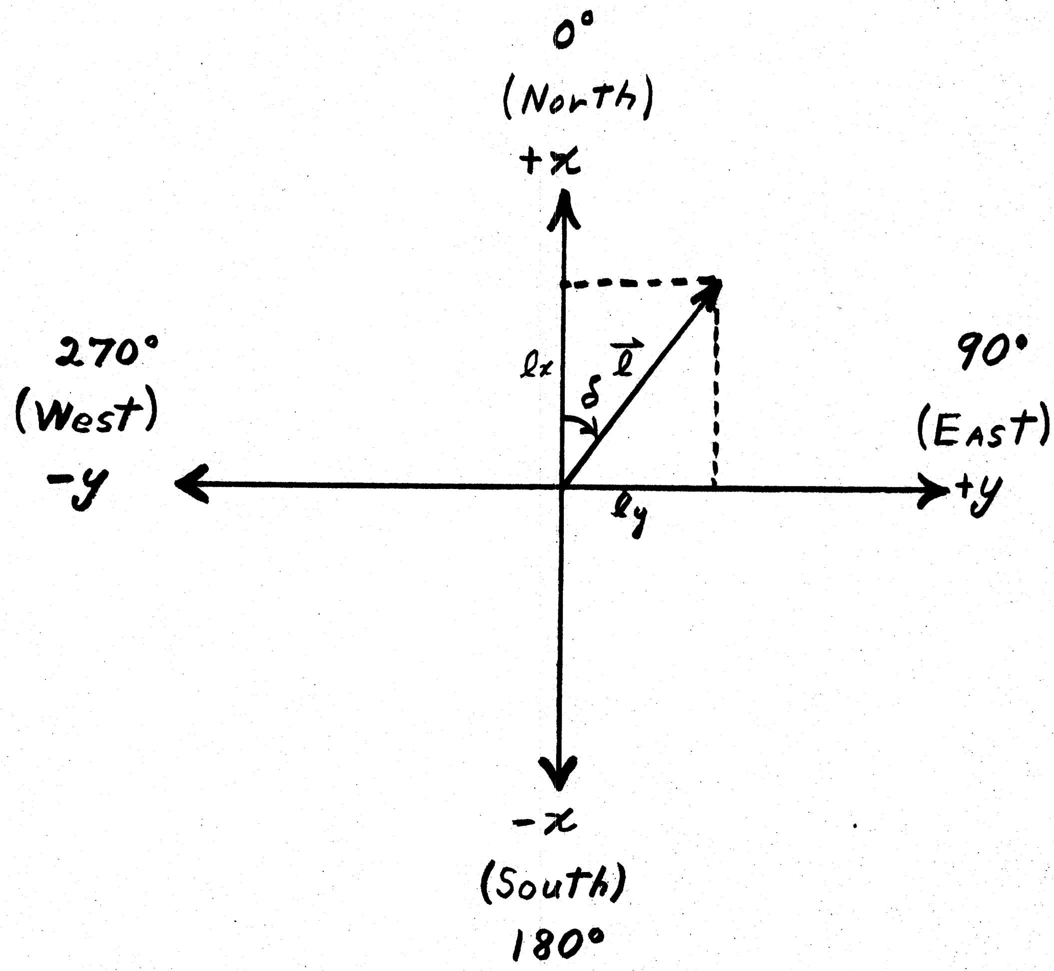

Fig. 6.—Relation between mariner's compass rose and coordinate system used herein.

continuously recorded on the chart paper:

1. Ship heading, δ, in degrees.
2. Ship's position.
3. Time.
4. When each turn is initiated.
5. Sign of suppression voltage.
6. Magnitude of suppression voltage.
7. Potentiometer full scale range.
8. ℓ (distance between electrodes; i.e., signal cable length)
9. Date.

In determining current velocity the voltages V_{p1}, V_{p2}, and V_{p3} are determined from the recorder chart. The ship's headings δ_1 δ_2, and δ_3, corresponding to V_{p1}, V_{p2}, and V_{p3}, are read from the ship's compass. These values for V_p and δ, along with the proper values of ℓ and H_z, are put into the above equations to calculate v_x and v_y. ℓ is found by measuring the distance between the two electrodes of the outstretched signal cable. H_z is a function of geographical location; it can be determined from tables.[6] Of course, H_z is considered constant during any one current measurement; it can in fact be considered constant over large geographical areas.

It was noted above that the ship's course should be held constant for approximately six minutes. If it is held for less than six minutes, good average values of the V_p's will not be obtained. On the other hand, if it is held for more than six minutes the ship may move into an area where the surface current velocity is different than what it was where the set of courses was initiated. There is always the possibility that the current regimen has such fine structure that the ship is not in one current long enough to make a velocity measurement. When this is the case it is often helpful to set out a marker and tow the GEK past the marker three times in three different directions; in this manner the current velocity at a precise location can be measured with a fair degree of accuracy.

For the case when $\overline{\ell}$ is perpendicular to $\overline{v}$ we find that $V_I = v\ell H_z$. An average value of H_z for Lake Michigan is 5.95×10^{-5} weber/m^2. If one were measuring a 0.5 mph current under these conditions, with $\ell = 100$ m, V_I would be 1.5 mv. If V_e is constant to ± 0.3 mv, then V_I could be measured with an accuracy of $\pm 20\%$.

RESULTS OF TESTS

The Freshwater GEK was tested four times in the open water of Lake Michigan near Grand Traverse Bay. On each occasion a

deep (15 meter) and a shallow drogue were set out and their initial position was determined (± 1/4 mile) by sextant fix. As the drogues drifted with the current, the instantaneous surface current velocity near the surface drogue was measured several times with the GEK. Both drogues moved in the same direction, the subsurface drogue moving less than half the distance of the surface drogue during the time interval; this is in accordance with the assumptions on which the equations of the last section were developed. The instantaneous surface current velocities, by GEK, were calculated using those equations; the results are tabulated along with average surface current velocities, by drogue, in Table 1. There are insufficient data to merit a statistical analysis. However, there is sufficiently close agreement between GEK and drogue measurements to conclude the applicability of the electromagnetic method to the type of system described in the section on electromagnetic effects.

A trace of the GEK chart showing the voltage, V_p, vs. time (position) curve for three successive ship headings in open water is included as Chart 1. The small high-frequency fluctuations in V_p are thought to be due to sporadic changes in V_e. The large scale changes in V_p are electromagnetic effects.

<u>Within the confines of the bay</u> no simple agreement between drogue and GEK data was observed. Most of the time the total

TABLE 1

INSTANTANEOUS SURFACE CURRENT VELOCITIES, BY GEK

Date	Position	Time	GEK Instantaneous Current Velocity		Drogue Avg. Current Velocity over Time Interval	
			Direction	Mph	Direction	Mph
8/8/62	4.2 miles, 26° from Grand Traverse Light	1:15 p.m.	158°	0.36		
		1:45 p.m.	120°	0.40		
		2:15 p.m.	128°	0.38		
		Mean	135°	0.38	148°	0.28
8/10/62	5.3 miles, 31° from Grand Traverse Light	11:30 a.m.	231°	0.18		
		12:05 p.m.	246°	0.12		
		1:15 p.m.	276°	0.24		
		Mean	251°	0.18	241°	0.20
8/14/62	4.0 miles, 34° from Grand Traverse Light	12:20 p.m.	51°	0.42		
		12:55 p.m.	48°	0.38		
		Mean	50°	0.40	54°	0.43
8/16/62	3.75 miles, 38° from Grand Traverse Light	11:25 a.m.	62°	0.14		
		12:20 p.m.	70°	0.18		
		12:55 p.m.	98°	0.28		
		Mean	77°	0.20	84°	0.20

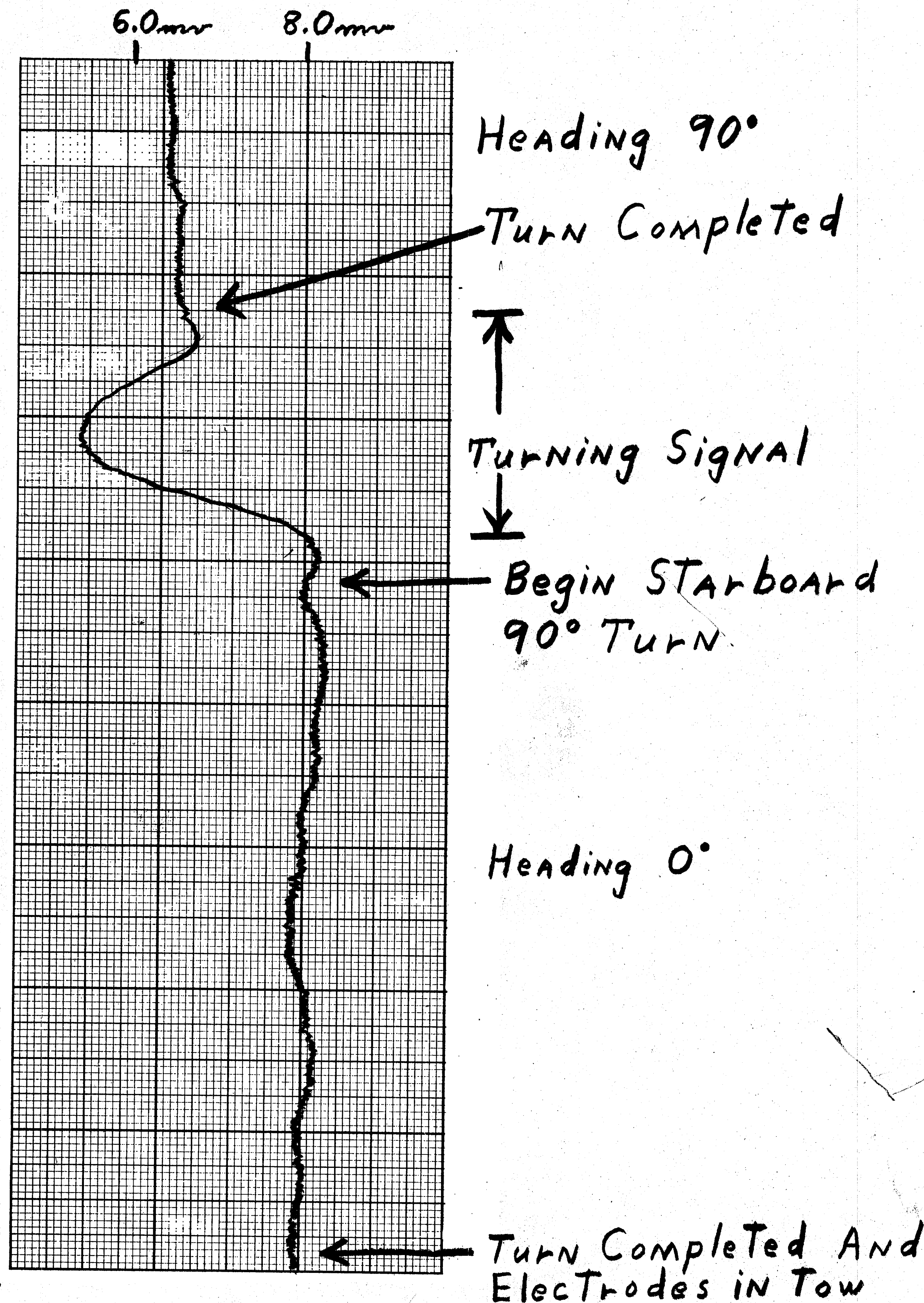
6.0mv
8.0mv
Heading 90°
Turn Completed
Turning Signal
Begin Starboard 90° Turn
Heading 0°
Turn Completed And Electrodes in Tow

CHART 1. (CONT.)

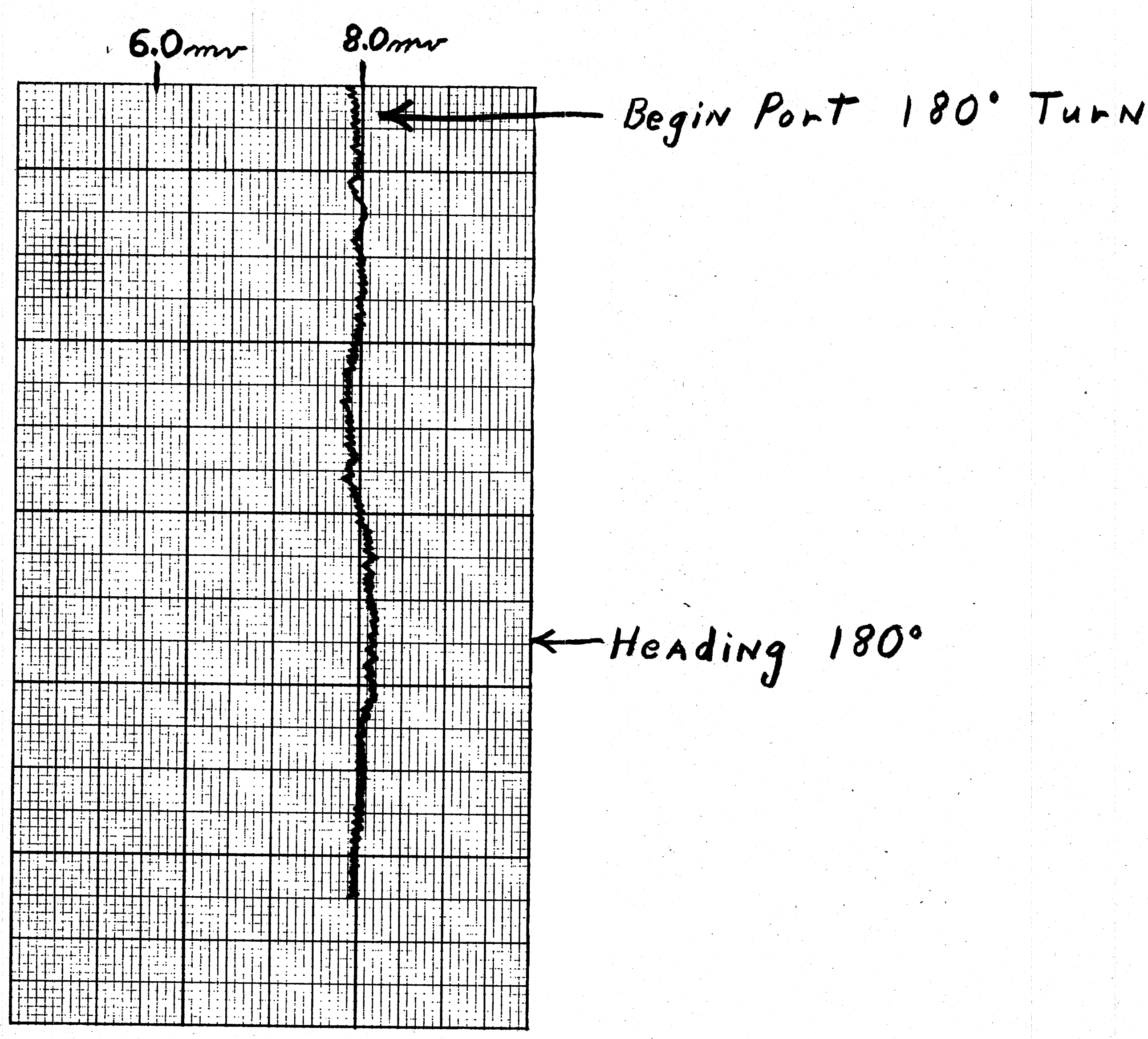

Chart 1.—A sample Freshwater GEK chart giving Vp vs. time for three successive headings. The turning signal for the 180° turn from 180° to 0° has been omitted. The difference in potential between curves for 180° and 0° headings is zero; that is, the current velocity has no west or east component. V_e is the voltage at the mid-point between these two curves; it is 8 mv here. The velocity $\vec{v}$ for this example, as calculated from the equations developed in the section on "Electromagnetic Effects," is: $\vec{v} = \vec{i}v_y \approx \vec{i}$ (0.6 mph) = 0.6 mph—north. In this instance there is no independent current velocity measurement to compare with the 0.6 mph—north value obtained by the electromagnetic method. We can conclude only that the difference between the drift velocity of the cable and the velocity of the water through which the cable is being towed is 0.6 mph—north (neglecting ohmic potential drops). The GEK measures the relative difference in velocities between the water at the surface and that at the cable depth.

e.m.f., V_p, changed sporadically in a nonsensical manner. Laboratory tests suggested that V_e was remaining constant, within the tolerable ±0.3 mv, so it was concluded that the changes in V_p were due principally to electromagnetic effects. Deep and shallow drogues were set out together on a number of occasions; they often moved in different directions, indicating that the subsurface water at a location was moving in a direction different from that of the surface water at that location.

It was also noted that surface drogues set out within a quarter of a mile of each other often moved in different directions as well as at different speeds; there was a complex current regimen which was too fine in structure for the application of the electromagnetic method. The existence of subsurface currents in addition to the complex surface current regimen could give rise to unpredictable values of V_I; this would account for the nonsensical changes in V_p.

On July 11, 17, and 23, and on August 1, 1962, very intense simple local currents were discovered in the southern portion of the West Arm of the bay. On July 11 the GEK was towed four times from east to west and three times from west to east through a region in which very intense electromagnetic effects were recorded. See Chart 2. The effects were unquestionably electromagnetic in

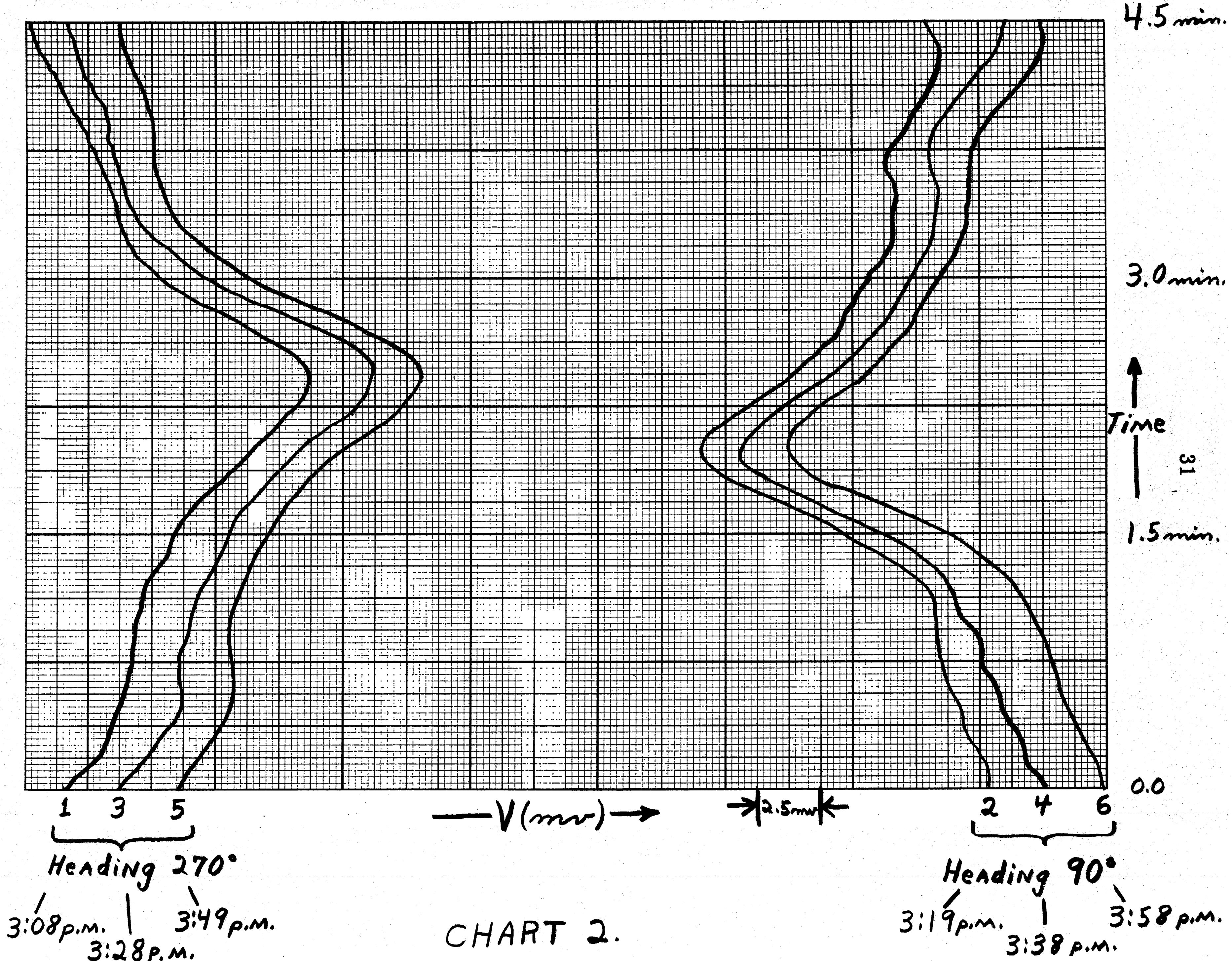
4.5 min.
3.0 min.
1.5 min.
0.0
Time
V (mv)
2.5 mv
1 3 5
Heading 270°
3:08 p.m.
3:28 p.m.
3:49 p.m.
2 4 6
Heading 90°
3:19 p.m.
3:38 p.m.
3:58 p.m.

CHART 2.

nature; the voltage vs. position curves corresponding to east-to-west traverses were mirror images of those curves corresponding to west-to-east traverses. The curves took the form of sharp peaks, the distance between successive mirror-image peaks being more than 13 mv. This represents an induced signal, V_I, of at least 6.5 mv., which, if the equations of the section on Electromagnetic Effects are applied, implies current velocities of at least 2.2 miles per hour. Surface drogues set out in the current did not move, perceptibly, during a time interval of 4.5 hours. No subsurface drogues were set out. It was concluded that the current was below the surface; the equations of the last section, then, would not apply, but it is not unreasonable to conclude that the magnitude of the current velocity was 2.2 miles per hour or greater. Similar currents were measured on July 17 and 23 and on August 1. They were weaker, but three or more traverses in each instance showed the same characteristic mirror-image peaks. Unfortunately, drogues were not set out on these occasions. Although there are insufficient drogue data to conclude anything about these currents, except perhaps magnitude, the repeated mirror-image peaks in the voltage vs. position curves are additional evidence implying the applicability of the electromagnetic method to freshwater research.

Traces of the mirror-image voltage vs. position curves are included as Chart 2. The curves have been displaced for ease of visualization. Curves 1, 3, and 5 correspond to ship headings of 270°; curves 2, 4, and 6 correspond to 90° headings. Curves 1, 3, and 5 are mirror images of curves 2, 4, and 6. This can be seen by subjecting one set of curves (1, 3, and 5 for example) to two successive reflections, one in the vertical axis and one in the horizontal axis. The time given with each curve is the time corresponding to the peak of the curve—the time at which the system passed through the most intense part of the current. The average difference in voltage between successive mirror-image peaks was 13.5 mv, indicating a value of V_I of 6.75 mv corresponding to the average peak height. The signal cable length was 100 m; towing depth, 25 m; and ship speed, 8 knots. The current was located two miles south of Marian Island in the West Arm of Grand Traverse Bay.

A third observation suggests a hitherto unpublicized application of the electromagnetic method. It was found that nearly sinusoidal voltage vs. time curves superimposed upon the normal GEK record (corresponding to straight-line runs) showed up on the GEK chart within a half-hour to one hour after a significant wind shift; the amplitude of the curves reached a maximum value within an hour to an hour and a half after the windshift, and the sinusoidal

curves had disappeared within three hours after the shift. After three hours a new current regimen corresponding to the new wind velocity had apparently set up. It is possible that eddies are formed on the surface during this transitional period. The diameters of these supposed eddies were estimated to vary from 50 to 1,000 meters. The maximum eddy current velocities were estimated at 0.5 mph. It may be possible to design special GEK cables for the sole purpose of studying current regimens under conditions of windshift. Tests under simulated conditions in a tank in the laboratory might also shed more light on this subject.

Most of the testing of the GEK was carried out in water of depths greater than 100 m. No attempt was made to determine a minimum depth limit for which the method is applicable. It is the author's opinion that the Freshwater GEK will work best in unconfined water more than 100 m deep; the minimum depth limit may be in the neighborhood of 25 to 50 m.

SUMMARY

A Freshwater Geomagnetic Electrokinetograph for measuring surface current velocities from a ship under way in large bodies of fresh water, such as the Great Lakes, has been developed. An antimony-antimonous oxide electrode has been designed for use with

the Freshwater GEK; the net electrochemical potential of an electrode pair of this design remains constant within the tolerable ±0.3 mv during each current velocity measurement. An equation, which relates surface current velocities to e.m.f. signals, has been derived on the basis of electromagnetic theory. The Freshwater GEK has been tested in the Grand Traverse Bay region of Lake Michigan; instantaneous current velocity measurements by GEK compare favorably with average current velocity measurements by drogues. Other data from the GEK also imply the applicability of the electromagnetic method to freshwater research.

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APPENDIX

FABRICATION OF ELECTRODES

During the past year a technique for the fabrication of electrodes has been developed. This procedure is recorded in detail here because of the difficulty involved in producing a set of electrodes with a sufficiently constant electrochemical potential. The author has produced many acceptable pairs of electrodes by strictly adhering to this procedure.

A. Necessary apparatus.

1. Melting apparatus.

    a. Ring stand—base and rod.

    b. Test tube clamp to attach to ring stand (for supporting test tube in which Sb is melted)—must be capable of withstanding considerable heat.

    c. Fisher (Meaker) burner and gas line.

    d. Test tubes—pyrex—(20 x 150 mm) without lip (to be used as melting pots).

    e. Pliers for loosening test tube clamp when hot.

    f. Spring-type test tube clamp for removing hot test tubes from clamp.

2. Dipper for adding granular Sb to melting pot. A test tube (later to be referred to as test tube 1) and clamp can be used as a dipper. The clamp, functioning as a handle, is

necessary since the dipper is held directly over the Fisher (Meaker) burner flame while adding granular Sb to the melt.

a. A screw-type, rather than spring-type, clamp is preferred.

b. Test tube—pyrex—(20 x 150 mm) without lip.

3. Casting mold (test tube 2), and casting assembly. The molten Sb is poured from the melting pot into a <u>hot</u> pyrex test tube and allowed to cool and solidify therein.

a. Test tubes—pyrex—(12 x 75 mm) with lip.

b. Two spring-type test tube clamps for removing hot test tubes from the casting assembly.

c. Cast iron lead-melting pot which, after having had a 1/2'' hold drilled through the bottom at the center, can be inverted and used for supporting the test tube. The test tube (test tube 3) is inserted bottom first through the hole and is supported by its lip. The flames of four Bunsen burners are directed from below into the pot, at the bottom of the test tube. The pot serves to concentrate and confine the flames to the neighborhood of the test tube, the object being to maintain a very high uniform temperature at all points on the test tube's surface. See Figure 1.

d. A tripod ring stand for supporting the inverted melting pot.

e. (1) Cooling tank; glass or pyrex container with an approximate volume of 1 liter. Distilled water is used for cooling the slug. (2) Cover for cooling tank.

4. Miscellaneous items.

a. Filter paper to protect slug from contamination while breaking away pyrex mold.

b. Reagent grade, granular, antimony metal.

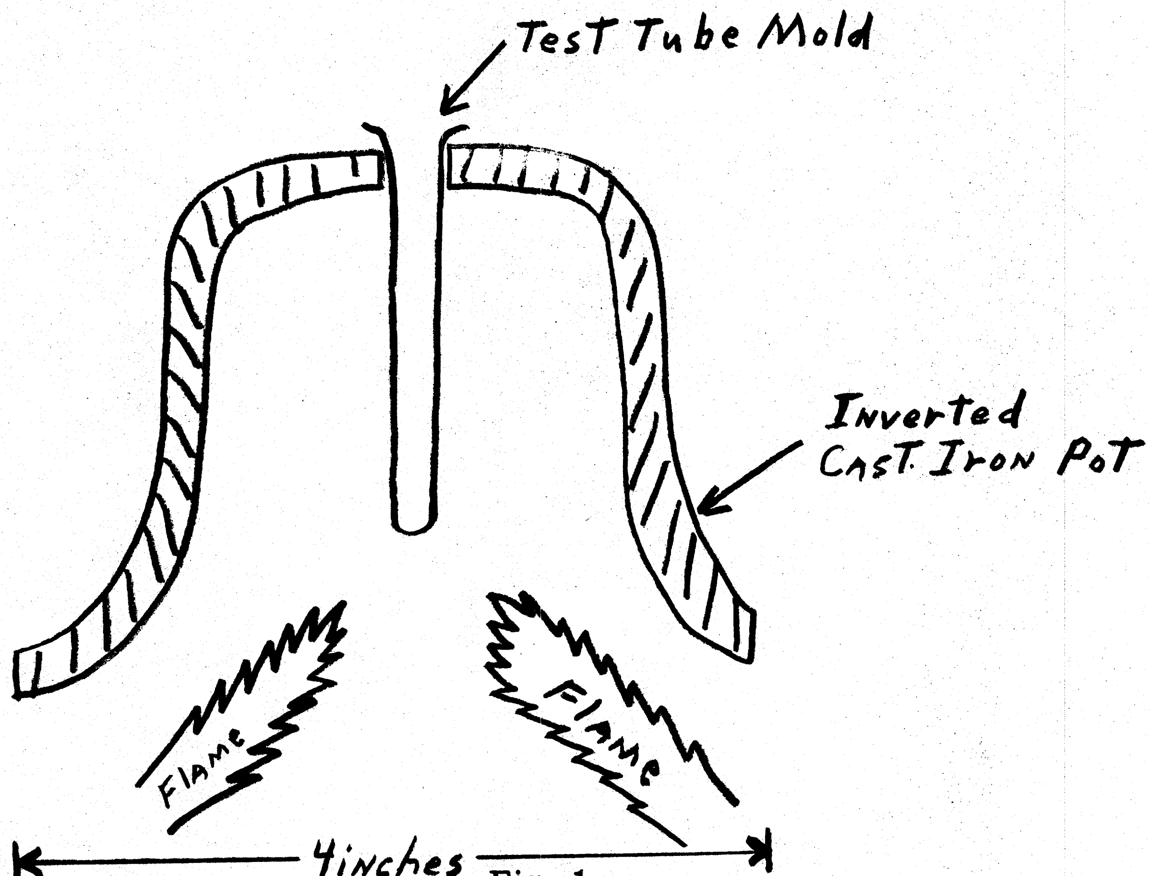

Fig. 1

c. Gas as fuel for Bunsen burners.

d. Compressed air.

B. Necessary glassware, preparation of apparatus, and casting of antimony slug.

1. Glassware necessary for the fabrication of one electrode slug.

   a. 1 - 12 x 75 mm pyrex test tube with lip.

   b. 2 - 20 x 150 mm pyrex test tubes without lip.

   c. 1 - 1 liter pyrex beaker.

   d. 1 - 6'' watch glass for covering beaker.

2. Preparation of apparatus.

Dissolve 20 grams of Alconox in 2 liters of warm tap water. Wash beaker and test tubes in this cleaning solution (using clean test tube brushes). Rinse with warm tap water. Rinse thoroughly in distilled water. Dry slowly over flame. Place test tubes on clean paper (24 cm filter paper for example) until ready to use them. Fill the beaker with distilled water and cover with watch glass until time to cool electrode slugs within.

Remove dust, etc., from top of casting assembly—particularly in the region of the hole. This can be done efficiently with a blast of air from the compressed air line.

Place a 20 x 150 mm test tube (tube 2) into the melting assembly clamp and adjust height of tube so its bottom will be in the hottest region of the Fisher (Meaker) burner flame.

Place a dry 20 x 150 mm test tube (tube 1) in the dipper clamp. Insert a 12 x 75 mm test tube (tube 3) into the casting assembly.

Prepare granular Sb for melting by pouring it repeatedly through an air jet to remove dust-size particles. It can also be poured from one clean piece of filter paper to another for the same purpose; this is repeated until the last piece of filter paper from which it was poured is free from darkening due to Sb dust. The melt will be cleaner if these particles are removed. Fill the dipper with Sb.

3. Casting antimony slug.

Place tube 2 over the Fisher (Meaker) burner such that the bottom of the tube is in the hottest region of the flame. Pour 2 to 3 cc Sb from the dipper (tube 1) into the melting pot; allow the Sb to melt and become red hot. As soon as the melt is red hot shake the melting apparatus until the surface slag collects on and adheres to the side of the test tube. Add Sb to the melt in quantities of 2 to 3 cc until the test tube is 1/3 full; each time Sb is added to the melt the melt must be allowed to become red hot, <u>after which time</u> the slag must be "shaken off."

It may be necessary to retighten the test tube clamp of the melting assembly periodically while melting the Sb.

The four Bunsen burners of the casting assembly are fired up before making the last two additions of the Sb to the melt, i.e., about 5 minutes prior to pouring the Sb from the melting pot (tube 2) into the casting mold (tube 3).

When the melting pot is 1/3 full of Sb, red hot, and all slag has been shaken off from the surface of the melt, the Sb is ready to be poured into the hot casting mold. This must be done with care since there will be a tendency for slag to be poured into the mold along with molten Sb. Any slag that does not adhere to the wall of the tube while pouring will come to the surface of the molten Sb and could be accidentally poured into the mold. This can be avoided if the following procedure is followed.

As soon as the melt is ready for pouring, turn off the Fisher (Meaker) burner and the four Bunsen burners of the casting assembly. The melting pot (tube 2) is left attached to the complete melting assembly (ring stand and clamp) while pouring. Tilt (incline) the melting assembly (with the top of the melting pot directly above the top of the casting hold) to an angle of approximately 10° above the horizontal. The forward extent of the flowing Sb should be about 1'' from the mouth of the test tube (see Figure 2).

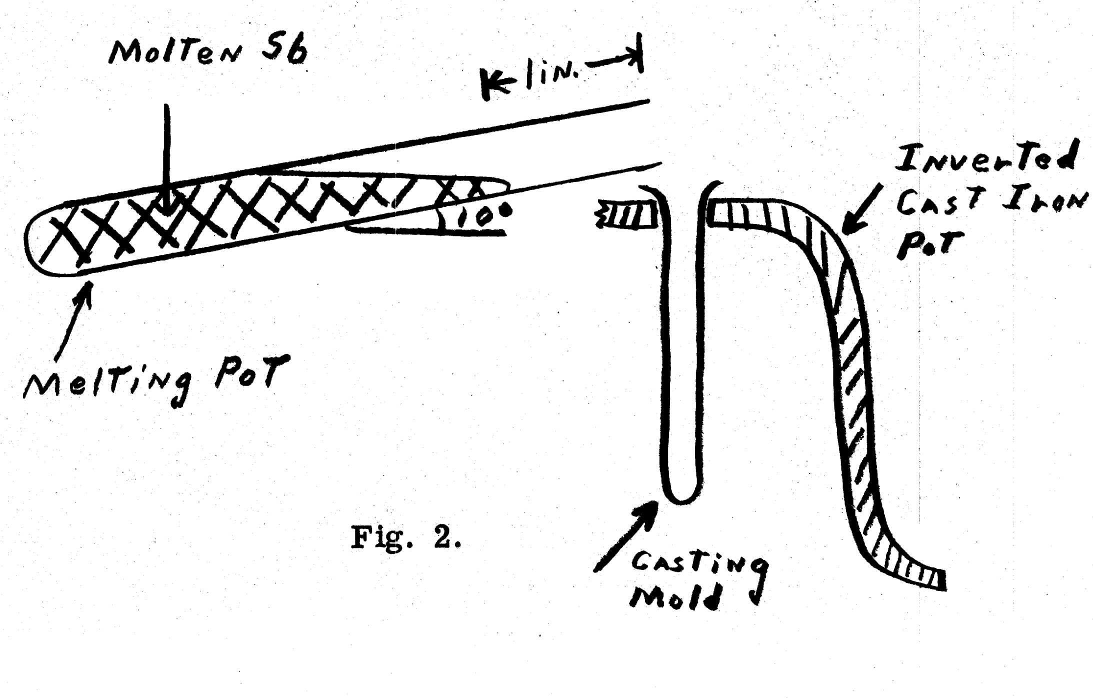

Fig. 2.

Hold the melting pot in this attitude until the surface begins to solidify. Surface slag will be trapped in the solid surface layer and the molten Sb can now be poured out from under this layer leaving the slag behind. Pour until the casting mold is full. This procedure requires patience and practice.

The melting assembly can be returned to the bench while allowing the Sb in the mold to solidify and cool for 3 to 6 minutes. At the end of this cooling time remove the mold from the casting assembly with a spring-type test tube clamp and thrust the mold into the distilled water in the cooling tank.

After the slug has been allowed to come into thermal equilibrium with the water in the cooling tank, remove it and place it on a piece of <u>clean</u> filter paper. Some of the glass mold may have broken away from the slug when it was thrust into the cooling tank. <u>Do not contaminate the slug by touching it with any foreign object, especially the fingers.</u> If the slug must be handled, hold it only by the upper end (the end at the mouth of the test tube).

Lay the slug on a piece of filter paper at the edge of a work table with the lip of the test tube hanging over the edge. See Figure 3.

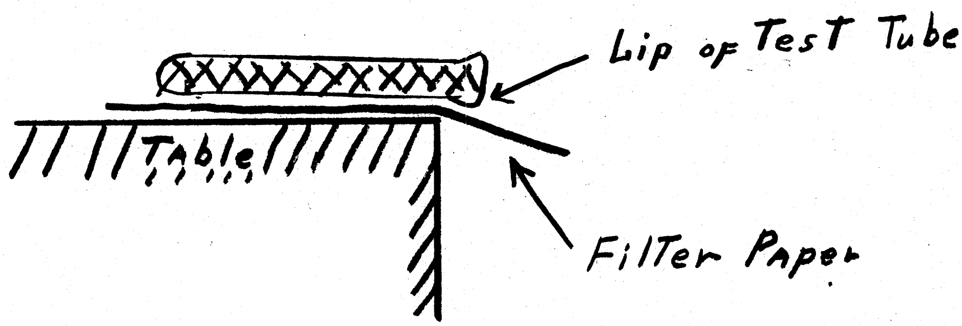

Fig. 3.

Crack the glass by tapping gently with a small hammer. If tapped with too much force, or especially if the lip of the tube is not hanging over the edge of the table, the slug can be easily cracked or broken. Solid antimony is very brittle.

Remove all large pieces of the broken tube from the surface of the slug. This can be done with the fingers if one is very careful not to touch the surface of the electrode slug. Small pieces of glass can be removed by rinsing the slug in distilled water.

The slug can be stored in a pH 7 buffer solution of Disodium Phosphate and Citric Acid. It is convenient to store a number of electrodes together in the buffer solution in a 100 cc large-mouth glass bottle. The cap is put in place so no air is trapped within.

C. Soldering leads to electrode slug and sealing soldered connection.

Remove electrode slugs from the buffer solution; use a narrow-nose forceps and make contact with the electrodes only at its upper end. Place the electrodes on a piece of clean filter paper.

Wash two 10 ml pyrex beakers in standard Alconox solution. Wash a 250 ml beaker in Alconox solution. Dry them both slowly over a flame.

Cut two 16 inch pieces of 20 gauge, solid, tinned, thermoplastic insulated, Cu hook-up wire. Strip away insulation from each end of each wire. Bend wire as in Figure 4.

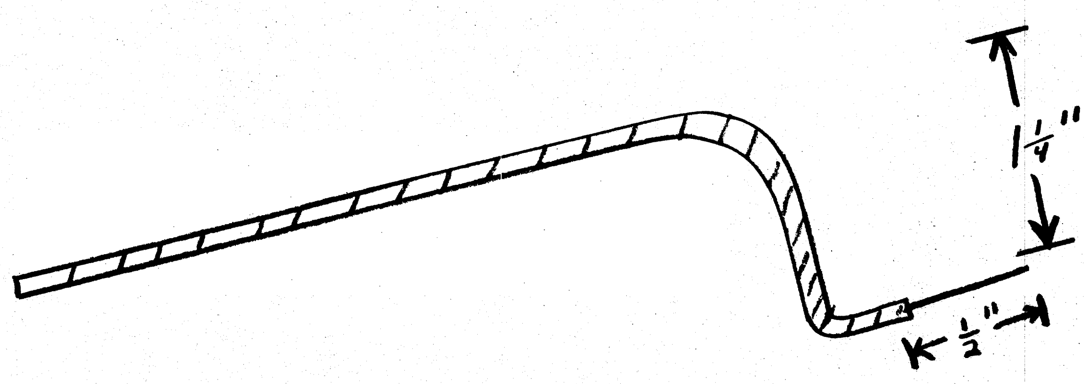

Fig. 4.

Place wire on Sb slug (Figure 5) for soldering.

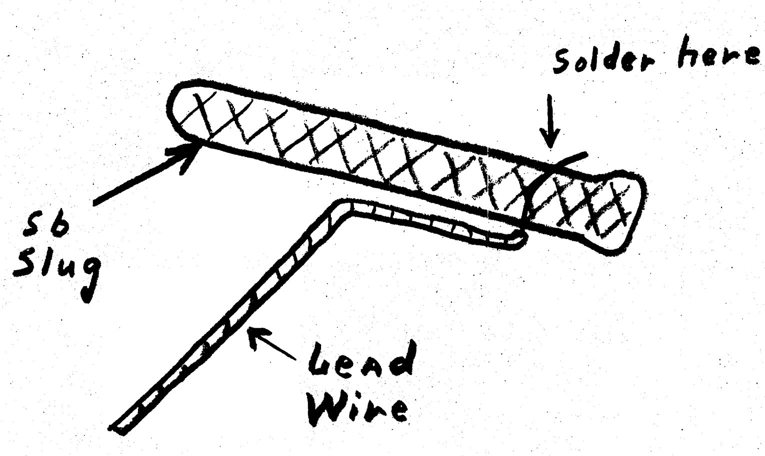

Fig. 5.

A 100 watt gun-type soldering iron is used for soldering the lead wire to the slug. The tip should be clean. Use Kester "Resin-Five" solder; alloy 60/40; diameter .062 in. Apply solder to hot tip until the collection of solder is about to fall from the tip. Touch this drop of solder to the filter paper to remove excess resin flux. Apply tip to wire in contact with slug and hold steady for about 30 seconds. Remove iron, leaving drop of solder in place, and allow to cool. This joint will not be physically strong, but will be a good electrical contact.

The solder joint and exposed lead wire must be sealed to prevent contact with the electrolyte. Paraffin wax provides a good seal. The top of the electrode is inserted into a 10 ml beaker and the wire is wrapped around the outside of the beaker to support the electrode. See Figure 6.

1/4 pound pure, clean paraffin wax is then placed into a 250 ml pyrex beaker and heated over a Bunsen flame until melted. The melted wax is then poured layer by layer into the 10 ml beaker with slug inserted. Each layer should be about 1/8" thick, and should be allowed to solidify before the next layer is poured. The beaker is filled to within 1/8" of top. Upon cooling, the wax will contract. The level may be restored to within 1/8" of the top by adding a little more wax.

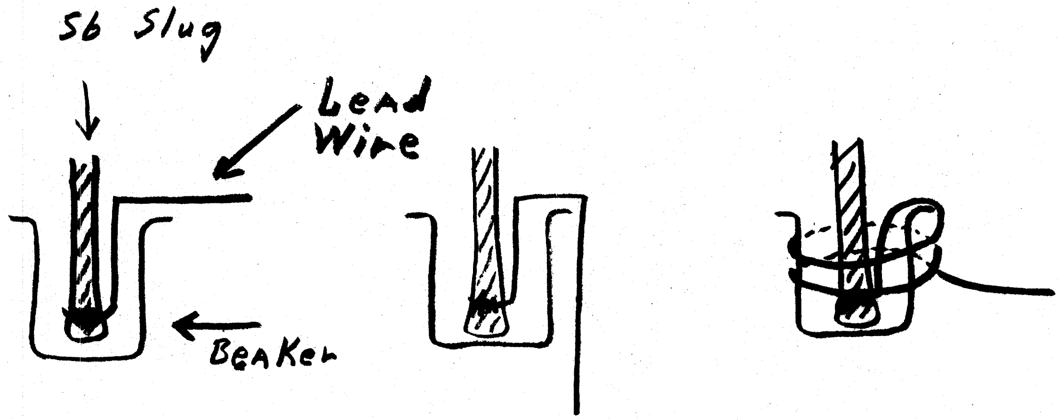

Fig. 6.

The completed electrodes should be connected, by soldering the ends of the lead wires together, and immersed in a pH-7 buffer solution (Disodium Phosphate-Citric Acid). They should be left in the buffer solution for at least 48 hours, to come to chemical equilibrium at a very low potential.

The electrodes may now be inserted into the electrode cases for the final phase of fabrication or may be stored in a pH-7 buffer solution.

D. Encasement of electrode slugs.

The lead wire wrapped around the small beaker is carefully unwrapped and is taped to the side of the beaker to hold it in place. The beaker should be dried before being wrapped with tape (tape—Scotch Brand No. 33 Electrical Tape). See Figure 7.

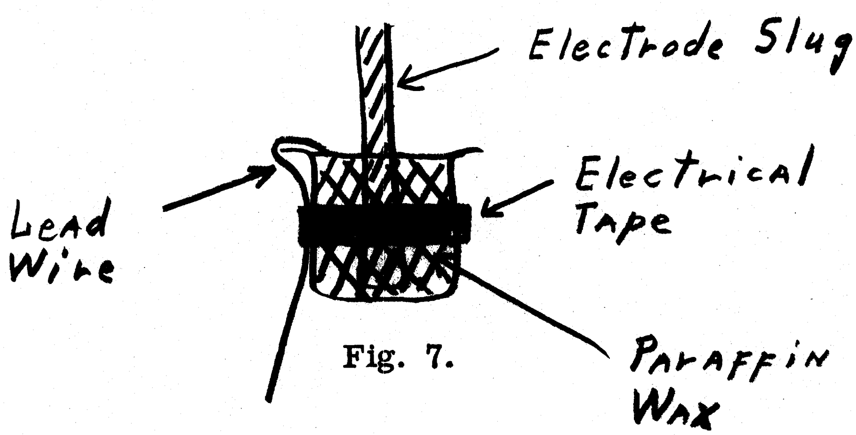

Fig. 7.

The electrode is inserted, with the lead protruding from the bottom, into an acrylic case (extruded acrylic tube 1-1/2" OD x 1/8" wall). See Figure 8.

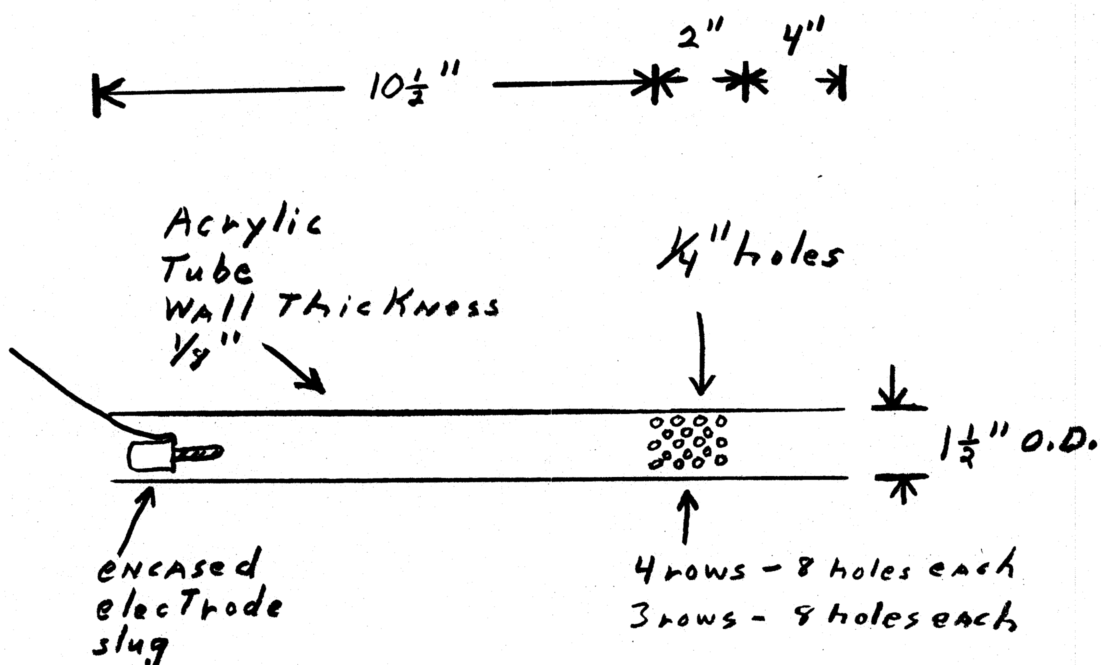

Fig. 8

A No. 7 solid rubber stopper (washed in Alconox solution) is pressed into the hole tightly—after wrapping a few turns of tape around the lead wire, to protect the insulation on the wire from the sharp edges of the end of the tube. The lead should be taped to the case by two wraps of tape (Scotch No. 33) around the case and wire. See Figure 9.

This entire end is then coated with a thin layer of paraffin wax to make it watertight. Tape is also wrapped around the tube so the end of the tube and the region between the end and 4 inches from the end is completely covered with from 3 to 5 layers of tape. This is to protect the wax seal and to give added protection against leakage.

Mount the electrodes open end up in two test tube clamps on one ring stand. See Figure 10.

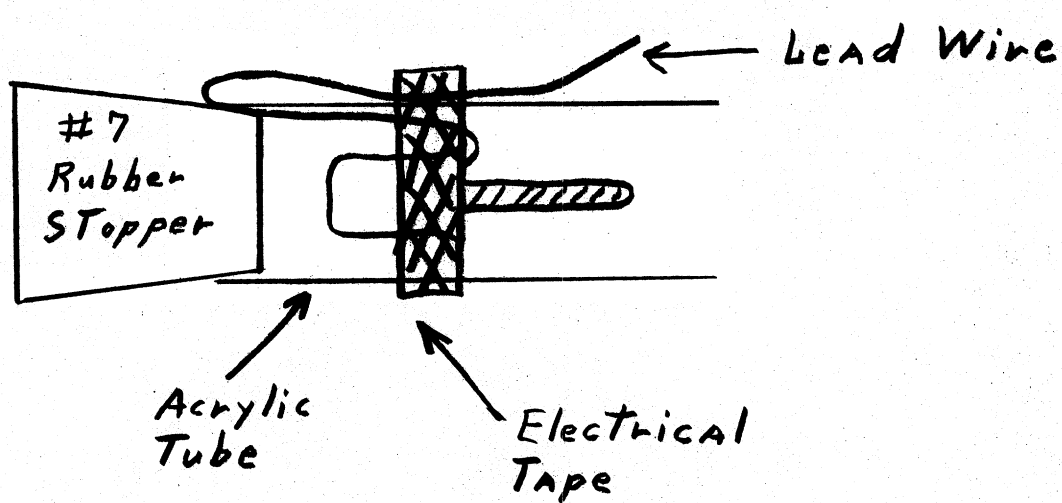

Fig. 9.

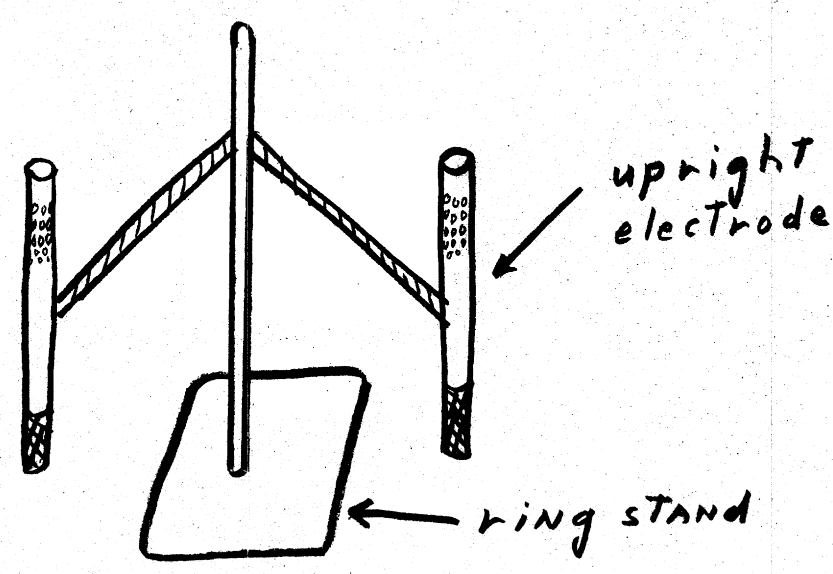

Fig. 10.

Stir 25 grams powdered agar into 800 ml of pH-7 buffer solution, in a 2 liter beaker, and bring to a slow boil over a Bunsen burner flame while stirring. (The measuring cups and beaker should be washed in Alconox solution and rinsed in distilled water.) The agar solution is allowed to boil very slowly for about 3–5 minutes before removing the flame. The agar has a strong tendency to boil out of control so the heat must

be carefully controlled. A water bath can be used for heating the agar solution.

Skim off bubbles from the surface with a piece of filter paper. Place the beaker in a sink of cold water and cool until the solution is just above its melting point. Before it solidifies pour the solution into the electrode cases until the solution level is up to the bottom of the holes in the sides of the electrode cases.

Bubbles at the surface may be cut away after the solution has solidified. Any solution which may have been poured through or may have flowed through the holes can also be cut away later with a small knife. Small particles may be washed away by swishing the electrodes forcibly back and forth in a buffer solution.

The electrodes may now be shorted together (via the leads) and stored in a buffer solution until ready for shipboard use.

E. Final electrode preparations.

Remove electrodes from the buffer solution and rinse in clean tap water or, preferably, the water in which they will be used. Do not shake or jar them for it is possible to separate the agar from the electrode slug.

The electrode is immersed in tap water (or <u>in situ</u> water), and stirred until all air bubbles have separated from the agar surface. Glass wool is immersed in the same water, squeezed to remove air bubbles, and stuffed into the open end of the electrode casing until glass wool is firmly packed to about 1/2" from the end of the casing.* A number seven rubber stopper is then pushed tightly into the end of the tube. This end region of the casing is now wrapped with plastic electrical tape—the wrapping is to prevent the stopper from popping out under conditions of towing. The electrodes, now ready to be attached to the GEK

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*Glass wool minimizes sporadic fluctuations in junction potential.

cable, can be stored for several months by shorting them together and immersing them in a pH-7 buffer solution.

When current measurements are not being made the GEK cable system is brought aboard the research vessel. To prevent the electrodes from drying out they are stored in in situ water without removing them from the cable. A pair of electrodes will last two months or more before the electrode resistance reaches 2,500 ohms. Longer electrode life may result from storing the electrodes in a buffer solution when the GEK is to be inactivated for longer periods of time than overnight. However, when this is done, it is necessary to tow the electrodes for an hour or so before the junction potentials become sufficiently stable.